TITLE: Improved Durability Aluminium Alloys for Airframe Structures

Improved Durability Aluminium Alloys for Airframe Structures

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ABSTRACT

The longevity of an airframe depends on its design, service conditions, and the durability and damage tolerance (DADT) of its constituent materials. Critical materials properties include corrosion resistance, fatigue resistance, fatigue crack growth resistance, as well as toughness. The present paper focuses on the metallurgical parameters that govern these properties and on recent developments aimed at improving the DADT of airframe alloys.

Resistance to structural corrosion of aluminium alloys for airframes depends on the nature and number density of the metastable hardening precipitates as well as on local alloying element concentration profiles, in particular in the vicinity of grain boundaries. The underlying corrosion mechanisms are discussed in the context of the development of two new corrosion-resistant products for use as upper wing skin panels (7449-T7951) or fuselage skin panels (6056-T78) respectively.

The fatigue resistance of structures is mainly governed by the fatigue resistance of joints, which is strongly related to technological factors (machining tolerances, riveting practice, etc.). Materials testing to simulate this behaviour is performed on open-hole specimens. Overall fatigue resistance of thick plate, for example, depends on ingot quality and rolling practices. Better understanding of these parameters has enabled the development of aerospace-quality 7010, 7050 and 7040 plate at thicknesses of up to 215 mm.

Finally, longevity of airframe structures depends on the materials' resistance to fatigue crack propagation and their fracture toughness. The metallurgical parameters that govern these properties are discussed and illustrated by recent results on fuselage and lower wing skin 2xxx alloys.

1. INTRODUCTION

Commercial and military aircraft are increasingly required to have longer service lives. As a result, considerable effort has been put into the study of ageing aircraft and the life extension of existing aircraft. However, it is clear that the airframes of the future need to be designed in the expectation of longer service lifetimes. Moreover, there is a cost-motivated drive towards increasing inspection intervals on new aircraft. As a result, there is a need for improvements in the durability and damage tolerance of airframe alloys.

A schematic illustration of the way in which materials properties can impact on the lifetime of a DADT-dominated metallic airframe part is presented in figure 1. Resistance to corrosion phenomena and fatigue life affect the time until initiation of a detectable flaw. Subsequently, fatigue crack growth rate, in more or less aggressive environments according to service conditions, dominates the growth of this crack. Finally, the residual strength of the structure, and thus the critical crack length, depends amongst other factors on the toughness of the base material.

In this paper, the metallurgical principles underlying these critical properties are discussed and illustrated with examples of recent or ongoing alloy development work (see AA compositions of alloys mentioned in table 1).

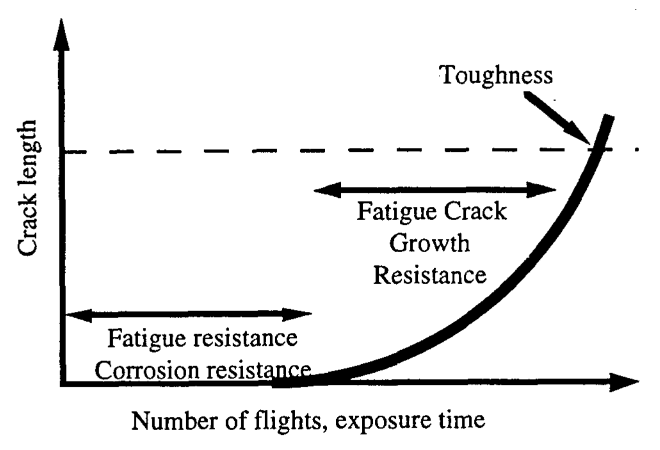

Figure 1. Schematic illustration of the influence of materials properties on the lifetime of an airframe structure.

Table 1. AA registered compositions of the recently developed alloys cited in this paper.

Alloy	Si	Fe	Cu	Mn	Mg	Cr	Zn	Zr
6056	0.7 1.3	0.50	0.5 1.1	0.4 1.0	0.6 1.2	0.05	0.1 0.7	<0.20 (Zr+ Ti)
7449	0.12	0.15	1.4 2.1	0.20	1.8 2.7	0.05	7.5 8.7	<0.25 (Zr+ Ti)
2024A	0.15	0.20	3.7 4.5	0.15 0.80	1.2 1.5	0.10	0.25	0.05

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2. CORROSION RESISTANCE OF AIRFRAME ALLOYS

Localised corrosion phenomena such as intergranular corrosion (IGC) and exfoliation corrosion can limit lifetimes of airframe structures, in particular by providing flaws or even pre-cracks for subsequent crack propagation. Sensitivity to IGC itself is a purely electrochemical phenomenon (see e.g.[1],[2]) determined by the existence of a microgalvanic couple between a grain boundary feature constituting a continuous anodic path with respect to a cathodic matrix (e.g. a continuous film of Al_3Mg_2 precipitation in Al-Mg alloys or a copper-depleted zone near the grain boundary for Al-Cu alloys). It is generally recognised ([3], [4]) that sensitivity to exfoliation corrosion almost invariably results from the conjunction of an aligned grain structure and sensitivity to IGC.

In order to avoid sensitivity to IGC of 2xxx or copper-rich 7xxx alloys it is necessary to devise a processing schedule that precludes the development of and/or reduces solute concentration profiles in the vicinity of grain boundaries. This can be achieved by limiting heterogeneous precipitation at grain boundaries during quenching or subsequent ageing (see figures 2 and 3 for application to the sensitivity to exfoliation corrosion of 7449 extrusions, and also [5]) and/or by overaging to equalise solute concentrations between grain boundaries and the matrix. The relative ease of desensitisation with ageing also depends on a suitable choice of alloy composition; for copper-rich 6xxx alloys, for example, there is an optimum ratio of Si:Mg:Cu that enables effective desensitisation to IGC for a minimal reduction in strength. This effect has been exploited in the development of 6056-T78 for fuselage skin and stringers, which combines a suitable composition window with a targeted overage (see e.g. [6], [7]). Another example of an optimised overageing treatment is the development of 7449-T7951 that allows a 10% increase in compressive yield strength with respect to 7150-T651 with significantly improved corrosion resistance (see figure 4 and [8]).

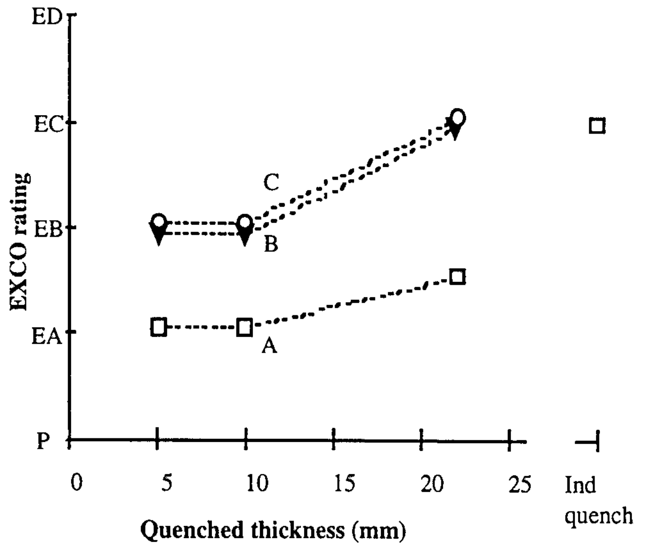


Figure 2. Influence of quench rate on exfoliation corrosion resistance of heavy-gauge 7449 extrusion (approx 1" flange thickness) in three near-peak tempers. Note the improvement in EXCO rating (P (best) -> ED (worst)) with increasing quench rate (decreasing quenched part thickness). This can be attributed to a concomitant reduction in heterogeneous precipitation at the grain boundaries during quench (see text). Temper A corresponds to a slight under-age at 120°C, tempers B and C respectively to a near peak age and a slight overage in an ageing cycle including a higher temperature step at 150°C.

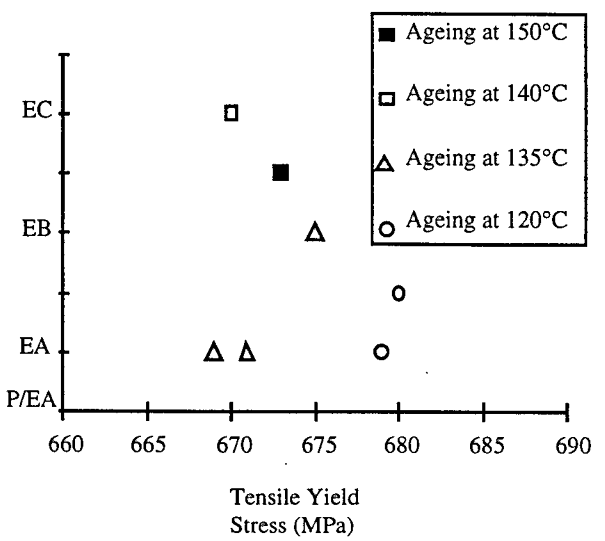
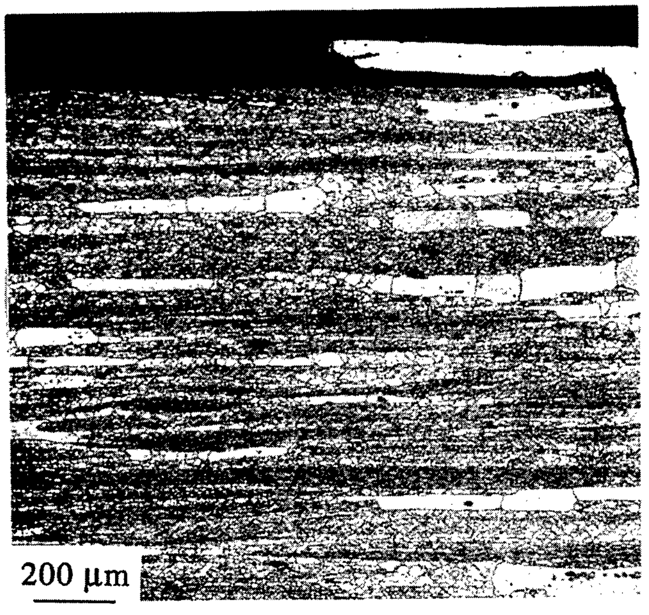
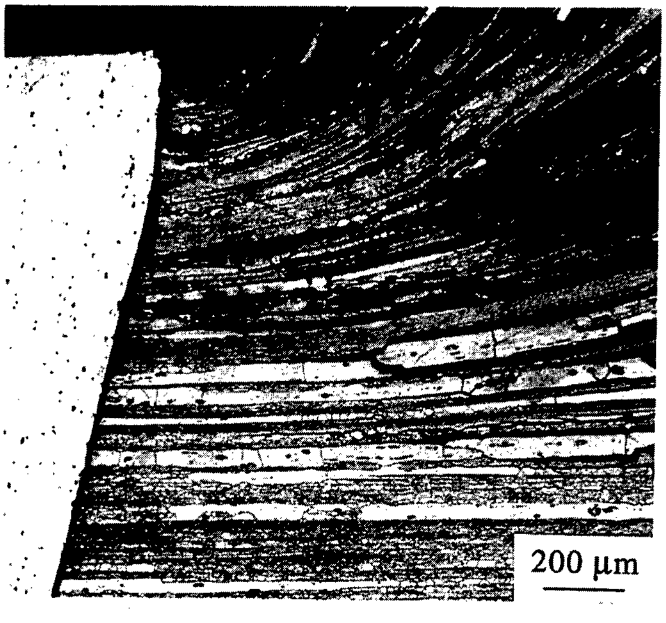


Figure 3. Exfoliation corrosion as a function of tensile yield stress for 7449 heavy gauge extrusion (sampled at th/10) aged to peak strength with ageing cycles with different peak temperatures. EXCO rating (P (best) -> ED (worst)) is degraded with higher temperature ageing, which can be attributed to an increased propensity for grain boundary precipitation (see e.g. Kirman[9]) and concomitant local solute depletion with ageing temperature. Note that the ageing treatment at 150°C (only) was preceded by a first step age at 120°C.



(a)



(b)

Figure 4. Comparison of corrosion in the vicinity of a 2117-T4 rivet in (a) 7449-T7951 and (b) 7150-T651 plate after 5 months exposure in a sea coast atmosphere at Salin de Giraud, on the Mediterranean coast (chromic etch of L-ST cross-section). The exposed surfaces correspond to the mid-planes of 38 mm (7449-T7951) and 25 mm plate (7150-T651). Note the considerably reduced sensitivity to exfoliation corrosion of the overaged 7449-T7951, which nevertheless has a compressive yield stress 10% higher than that of 7150-T651.

3. FATIGUE RESISTANCE

The fatigue resistance of structures is mainly governed by the fatigue resistance of joints, which itself is strongly related to technological factors. However, the material itself plays a role and fatigue tests on specimens containing one or two holes are aiming at evaluating the intrinsic materials fatigue resistance in its position in an assembly.

The fatigue resistance of these hole-containing specimens is related to the distribution of coarse intermetallic precipitates (their number density and more markedly their size) and to the yield stress of the material, both playing a role in the initiation stage[10]. It also depends on the fatigue crack growth behaviour of the material, which is discussed later.

Beside this main aspect of fatigue, it is necessary to assess the fatigue resistance of the bulk material[11]. Improved smooth specimen (K_t= 1) fatigue resistance of thick plate depends on ingot quality and rolling practices. Better understanding of these parameters has enabled the development of aerospace-quality 7010, 7050 and 7040 plate at thicknesses of up to 215 mm. An example of the effect of process modifications on a given alloy is given in figure 5. A model relating fatigue life and defect size was used to evaluate the different production practices on the fatigue resistance[12]. Below a certain pore size, the intermetallic precipitates become the predominant feature for initiation of fatigue cracks.

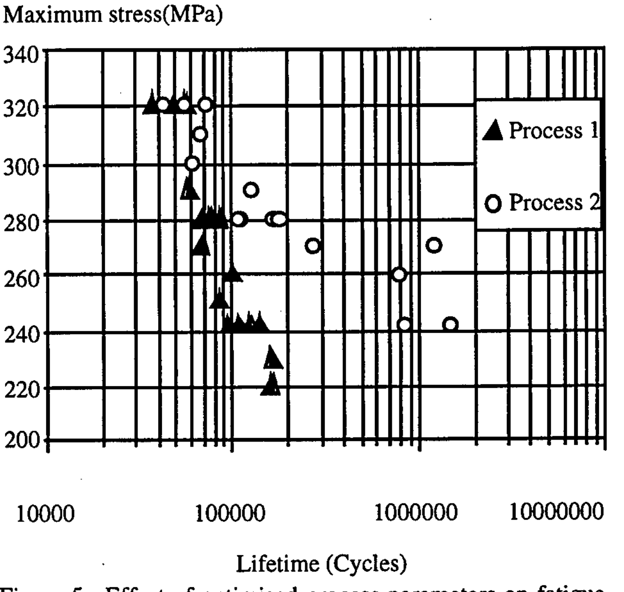


Figure 5. Effect of optimised process parameters on fatigue resistance of thick plate (7010-T7451 200 mm plate, R=0.1, Kt = 1).

4. FATIGUE CRACK GROWTH RESISTANCE

The design of many commercial aircraft lower wing and fuselage skins is limited by fatigue crack growth resistance and toughness. Currently, the alloy of choice for these applications is 2024-T351 or T3, but there is increasing demand for the development of an alloy with an improved balance of properties for these applications. Given the complex nature of the property compromise required for these applications, the replacement of 2024 is not a simple matter. As part of an R&D effort to develop an improved alloy for damage tolerance dominated structures, we have undertaken a background study on the microstructural paramaters that govern FCGR of 2024-type alloys. Some of the results of this work are presented in the following paragraphs.

The parameters mentioned in the literature as important with respect to crack propagation rates of aluminium alloys include (see e.g. [13, 14]):

- a beneficial effect of slip reversibility, which is affected by the nature of the hardening precipitates and dispersoids, and by the substructures;

- a detrimental effect of coarse intermetallic particles, particularly for higher ΔK values;

- the cyclic behaviour of the material.

In addition, closure and environmental effects must also be considered in the understanding of this behaviour.

In order to quantify some of the above mentioned effects, we have characterised the fatigue crack growth behaviour of model plates of 2024-type alloys in CCT specimens (sampled at quarter thickness, W = 200 mm, B = 5 mm, L-T orientation) at R = 0.05 or R = 0.5. Plates with a variety of dispersoid number densities (high, medium, low in figures 6 and 7) and extreme grain structures (largely unrecrystallised to completely recrystallised, and completely recrystallised with coarse grains) were processed and then characterised. With respect to their FCGR performance, the following conclusions can be drawn:

- the observed FCG rate increases with increasing dispersoid number density at R = 0.05 (see figure 6);

- FCG rate at R = 0.05 is lowest for the low dispersoid number density, coarse recrystallised grain material;

- there is little or no influence of recrystallisation rate on the FCGR of the high dispersoid density material.

In the tests at R = 0.5, the differences observed at lower R-ratio between coarse grain low dispersoid content plate, classical low dispersoid density plate, and medium dispersoid density plate are no longer significant.

These differences in FCGR are reflected in differences in crack propagation paths (see figures 8 and 9). Crack paths are extremely perturbed in the recrystallised, low dispersoid density plates, with locally well-defined planar crack surfaces and significant secondary cracking. For the higher dispersoid density plates (see e.g. figure 9) the crack paths are macroscopically very flat, though very locally perturbed. These characteristic differences in crack path are observed at both R-ratios.

These different paths can be attributed to the relative homogeneity of deformation as a function of dispersoid density (see e.g. [13, 14]). Relatively low dispersoid density allows planar slip over large distances, and thus crack paths that are very perturbed on roughly the scale of the grain size. Higher dispersoid densities homogenise slip, and thus favour macroscopically flat crack surfaces. The fact that the difference in crack propagation path is retained at R=0.5 but not the improvement in crack propagation rate of the low dispersoid density plate over the other 2024 plates implies that at least part of the difference in FCGR at low R-ratio is attributable to crack closure effects that are suppressed at the higher R-ratio.

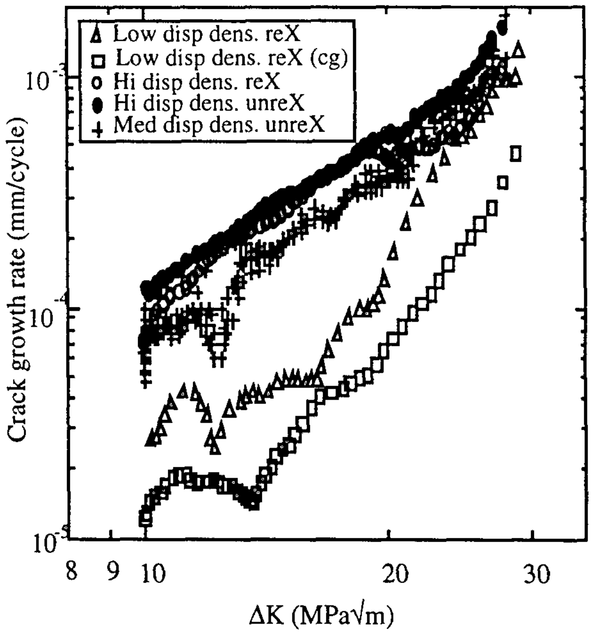


Figure 6. Comparison of fatigue crack growth rates at R = 0.05 as a function of crack growth rate for different 2024-type alloys (CCT specimens, sampled from 40 mm plate, different composition-processing variants). See text for discussion.

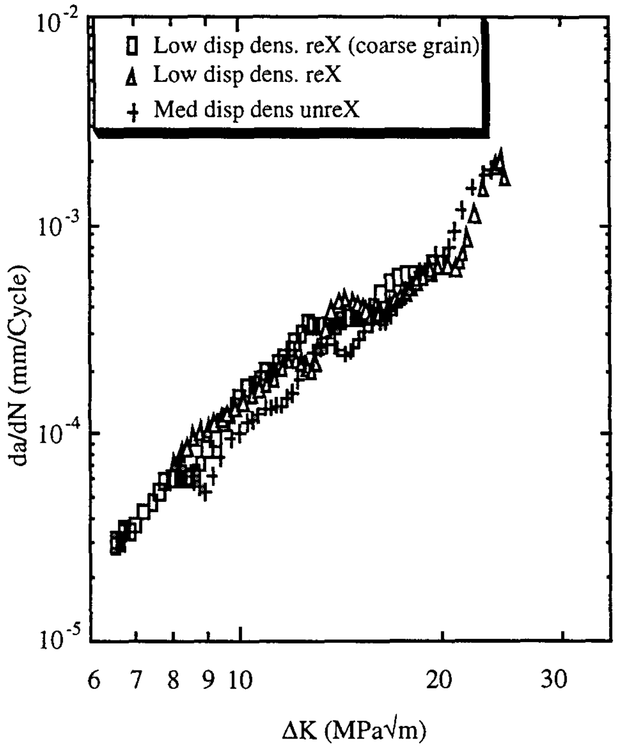
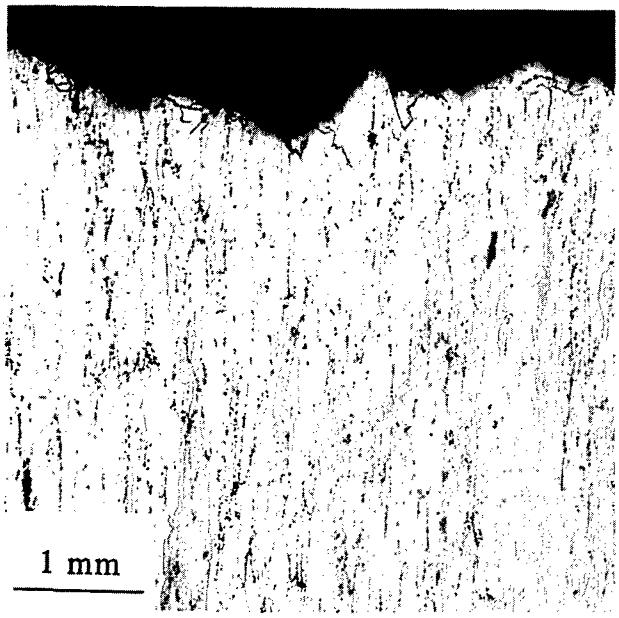
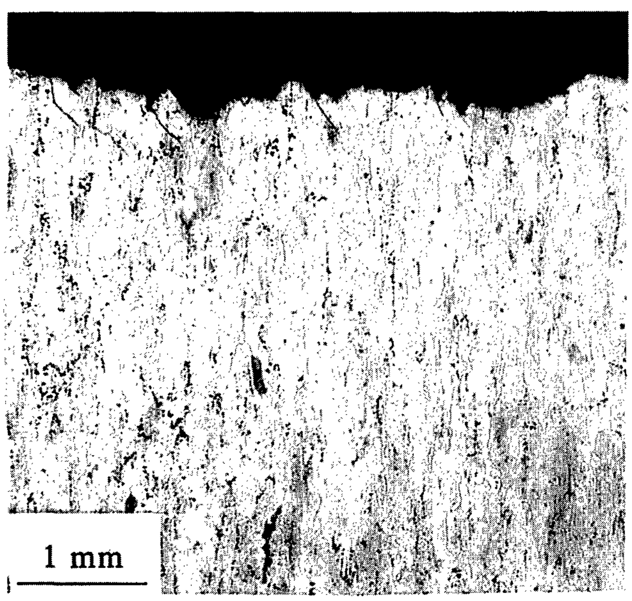


Figure 7. Comparison of fatigue crack growth rates at R = 0.5 as a function of crack growth rate for different 2024-type alloys (CCT specimens, different composition-processing variants). See text for discussion.



(a)

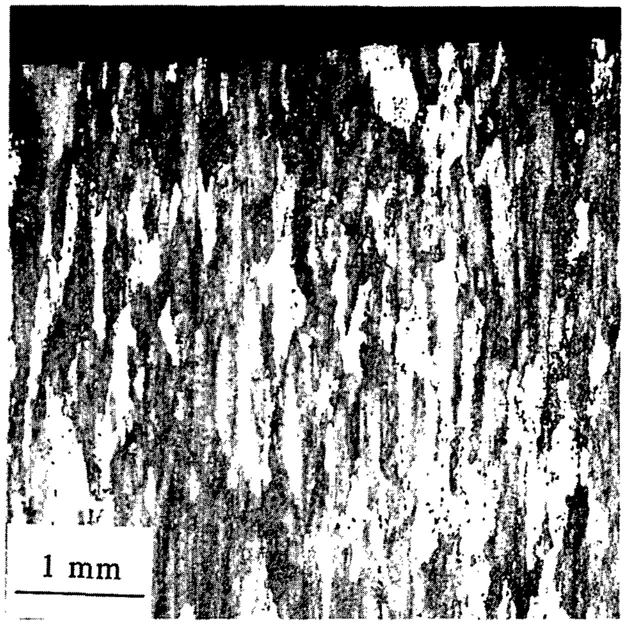


(b)

Figure 8. Crack paths at ΔK = 15 MPa√m in the low dispersoid density plates (L-T sections, after chromic etch): (a) recrystallised, coarse grain size, (b) recrystallised, classical grain size.

The same line of reasoning can also account for the improvement in FCGR at R = 0.05 for the coarse grain material. Coarser grains allow of slip over a larger scale, and thus render more marked the closure effects observed for the low dispersoid density plates. For the higher dispersoid density, the effect of modifying the grain structure is not detectable because slip is already homogenised by the dispersoids on a smaller microstructural scale.

These data, combined with similar results on other key properties for lower wing skin and fuselage applications, are currently being exploited in the design of a new lower wing skin product.



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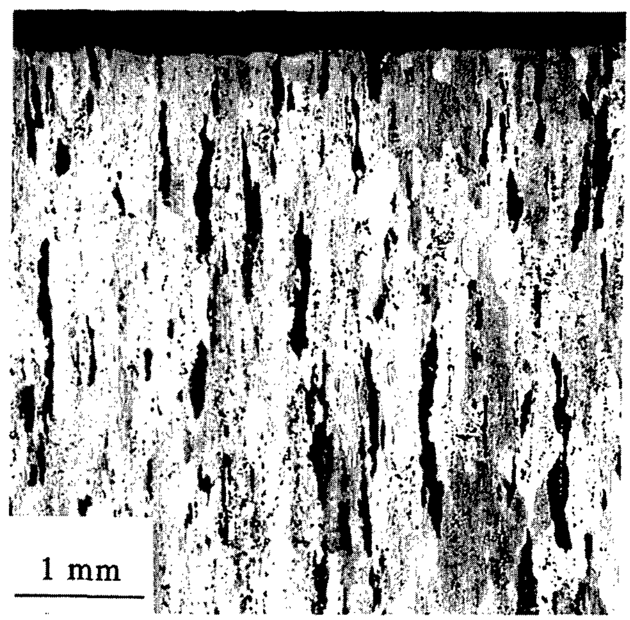

(b)

Figure 9. Crack paths at ΔK = 15 MPa√m in the high dispersoid density plates (L-T sections, after chromic etch): (a) largely unrecrystallised (b) largely recrystallised.

5. TOUGHNESS

The microstructural parameters that determine the toughness of aluminium alloys are well-described in the literature (e.g. [15], [16]). A recent example of the application of some of these principles is the development of improved toughness versions of 2024-T3 fuselage sheet. Improvements in processing schedule and composition that enable a reduction in the volume fraction of coarse intermetallic particles and dispersoids in 2024-type alloys have been identified. The corresponding improvements in materials properties are indicated in table 2.

Table 2. Typical properties of 2024A-T3 sheet compared with conventional 2024-T3 sheet (data for 1.6 - 3.2 mm sheet)

Property	Direction	2024A-T3	2024-T3
TYS (MPa)	L	340	350
	TL	300	320
UTS (MPa)	L	455	465
	TL	440	455
El (%)	L	22	19
	TL	24	18
K_{CO} / K_C(MPa√m)*	L-T	105 / 155	93 / 140
	T-L	100 / 150	90 / 130

* tested at W = 760 mm, $2a_O$ = 133 mm, calculated for W = 400 mm.

6. CONCLUSIONS

The development of improved alloys for DADT-dominated applications requires detailed understanding of microstructure-property relationships, some of which have been discussed and illustrated above. However, significant weight gains on new airframes will necessitate the simultaneous improvement of several such properties, each one not necessarily varying in the same sense with a given microstructural (process) modification. Clearly, close collaboration with airframe designers in order to quantify key property goals. Moreover, quantified metallurgical modelling of static and DADT properties of industrial wrought alloys is therefore a key tool in providing efficient responses to these property goals. Research efforts to this end are underway[17]. Application of the results of this R&D on an industrial scale requires both an understanding of the possibilities and limitations of industrial processing and continuous improvements in the mastery of the processing schedule.

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